

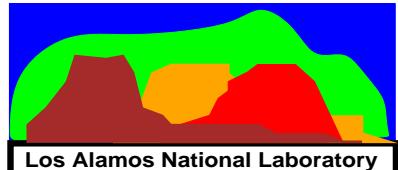
ATMOSPHERIC PRE-CORRECTED DIFFERENTIAL WATER VAPOR RETRIEVAL OVER MANY SURFACE TYPES

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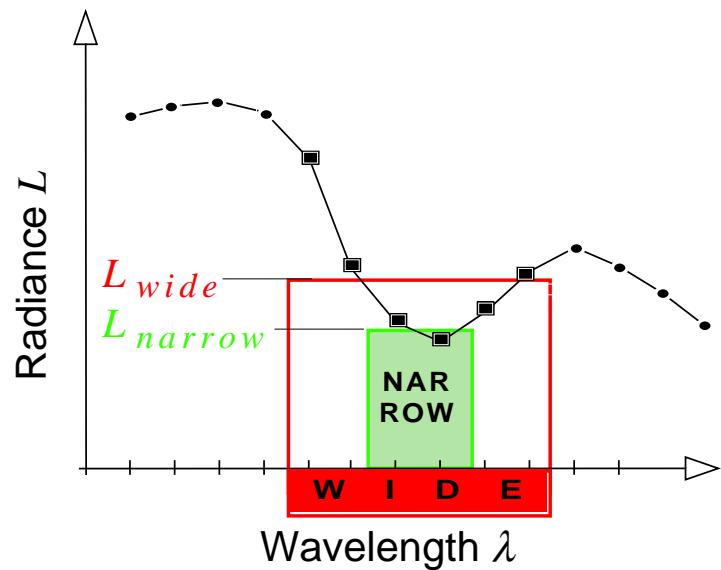
1. Derivation of the atmospheric pre-corrected differential absorption technique
2. Comparisons of the CIBR and APDA using a simple radiative transfer model
3. Comparisons of the CIBR and APDA for Variable water vapor and 562 reflectance spectra
4. Conclusions

EXISTING WATER VAPOR RETRIEVAL METHODS

1. Differential absorption techniques based on:
 - (a) Narrow-Wide (N/W) ratio between overlapping spectrally wide and narrow channels (Frouin et al, 1990)
 - (b) Continuum Interpolated Band Ratio (CIBR) between a measurement channel and the weighted sum of two reference channels (Green et al, 1989, Bruegge et al, 1990, Gao and Goetz, 1990a, and Carrére and Conel, 1993)
2. Non-linear fitting techniques which are based on spectral radiative transfer calculations (Gao and Goetz, 1990b, Green et al, 1993).

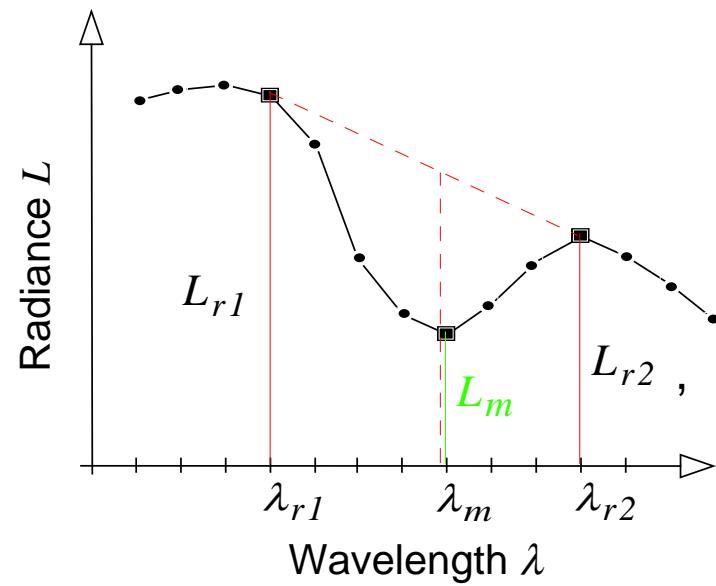


Narrow/Wide



$$R_{N/W} = \frac{L_{narrow}}{L_{wide}}$$

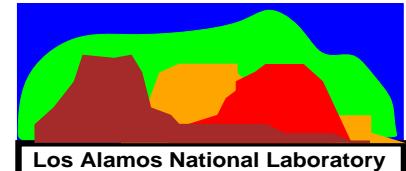
Continuum Interpolated Band Ratio



$$\omega_{r1} = \frac{\lambda_{r2} - \lambda_m}{\lambda_{r2} - \lambda_{r1}}$$

$$\omega_{r2} = \frac{\lambda_{r1} - \lambda_m}{\lambda_{r2} - \lambda_{r1}}$$

$$R_{CIBR} = \frac{L_m}{\omega_{r1} \cdot L_{r1} + \omega_{r2} \cdot L_{r2}}$$



ATMOSPHERIC PRE-CORRECTED DIFFERENTIAL ABSORPTION

DERIVATION:

STEP 1: The radiance L measured in channel i by a sensor is:

$$L_i = L_{g,i}T_{0,i}T_i(PW) + L_{p,i}(PW), \quad (1)$$

where

$L_{g,i} = \rho_{g,i}\frac{E_i}{\pi}$ is the upwelling radiance at the ground which would be measured if there was no atmosphere,

$\rho_{g,i}$ is the ground reflectance, E_i is the solar irradiance,

E_i is the solar irradiance, $T_{0,i}$ is the transmission of a dry atmosphere (sun to ground to sensor),

$T_i(PW)$ is the transmission (sun to ground to sensor) due to water vapor PW and $L_{p,i}(PW)$ is the path radiance.

STEP 2: Linear interpolation of radiance in measurement (m) channel:

$$L_m(PW) = [w_{r1}L_{g,r1}T_{0,r1} + w_{r2}L_{g,r2}T_{0,r2}]T_m(PW) + L_{p,m}(PW), \quad (2)$$

where

$$w_{r1} = \frac{\lambda_{r2} - \lambda_m}{\lambda_{r2} - \lambda_{r1}} \quad \text{and} \quad w_{r2} = \frac{\lambda_m - \lambda_{r1}}{\lambda_{r2} - \lambda_{r1}}. \quad (3)$$

STEP 3: Solve for $T_m(PW)$:

$$T_m(PW) = \frac{L_m - L_{p,m}(PW)}{w_{r1}(L_{r1} - L_{p,r1}) + w_{r2}(L_{r2} - L_{p,r2})} \quad (4)$$

STEP 4: Approximate $L_{p,m}$ with polynomial of second (or higher) order:

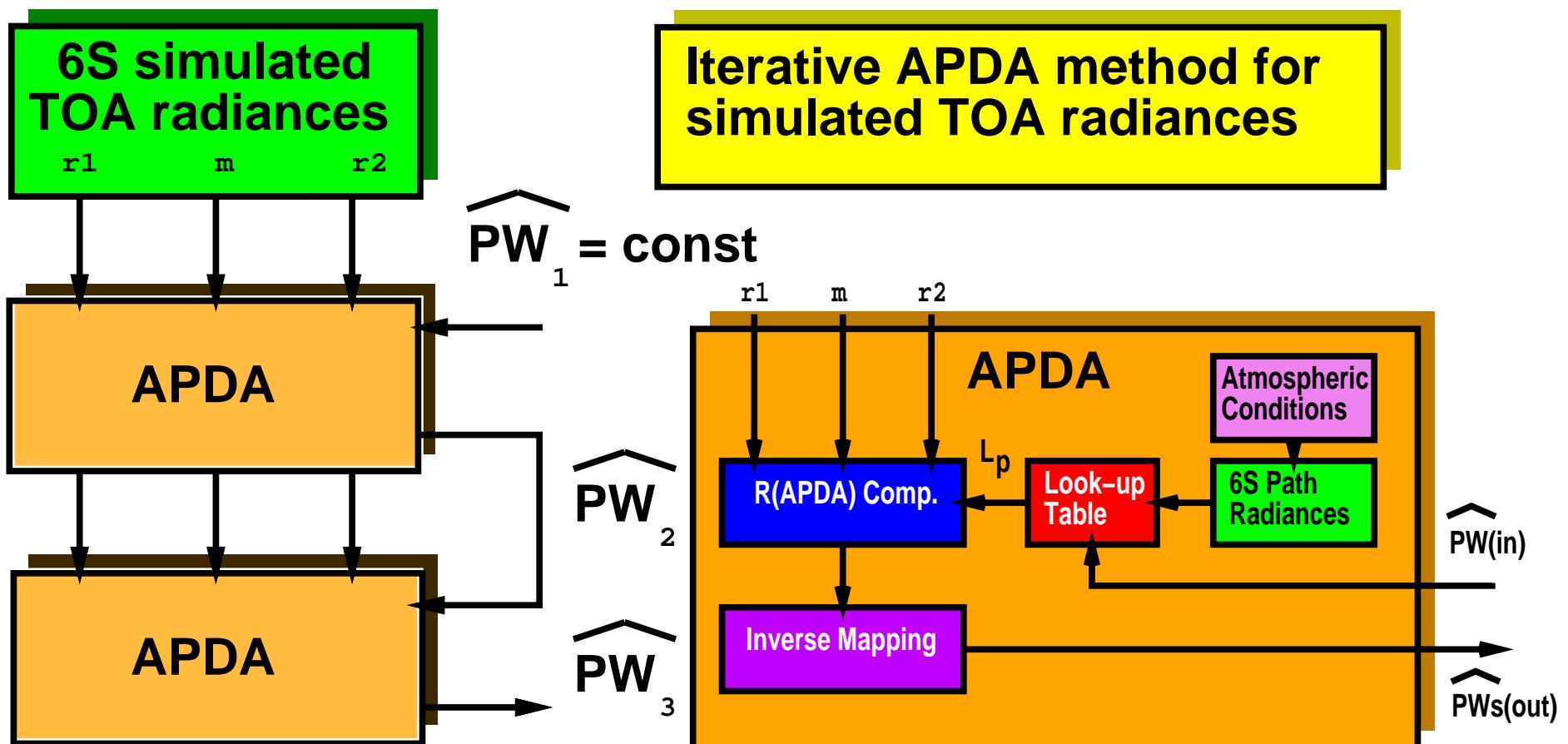
$$L_{p,m}(PW) = aPW^2 + bPW + c + L_{\text{adj},m}, \quad (5)$$

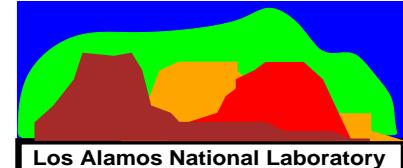
APDA Ratio:

$$R_{APDA}(PW) = \frac{L_m - (aPW^2 + bPW + c)}{w_{r1}(L_{r1} - L_{p,r1}) + w_{r2}(L_{r2} - L_{p,r2})}. \quad (6)$$



ITERATIVE APDA SOLUTION





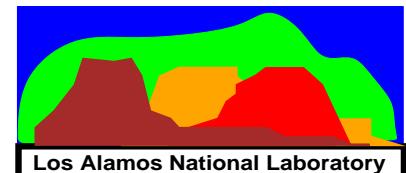
CONTINUUM INTERPOLATED BAND RATIO (CIBR)

DEFINITION:

$$R_{CIBR} = \frac{L_m}{w_{r1}L_{r1} + w_{r2}L_{r2}} \quad (7)$$

NOTES:

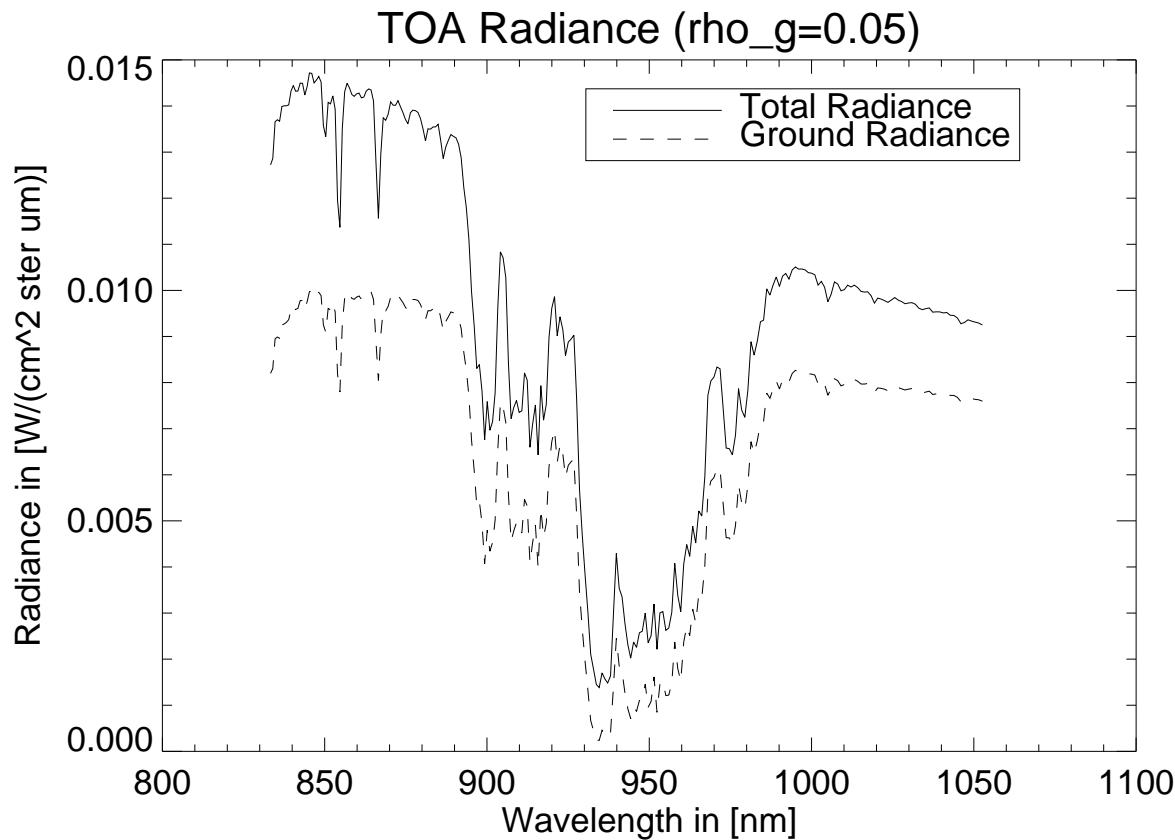
- The CIBR assumes that the underlying surface reflectance is linear over the range of wavelengths of interest.
- The CIBR works for highly reflective backgrounds (e.g. playas)
- Influence of path radiance for dark targets has been recognized since 1989 but has not been explicitly treated (except in non-linear fitting methods).



DARK TARGET CIBR:

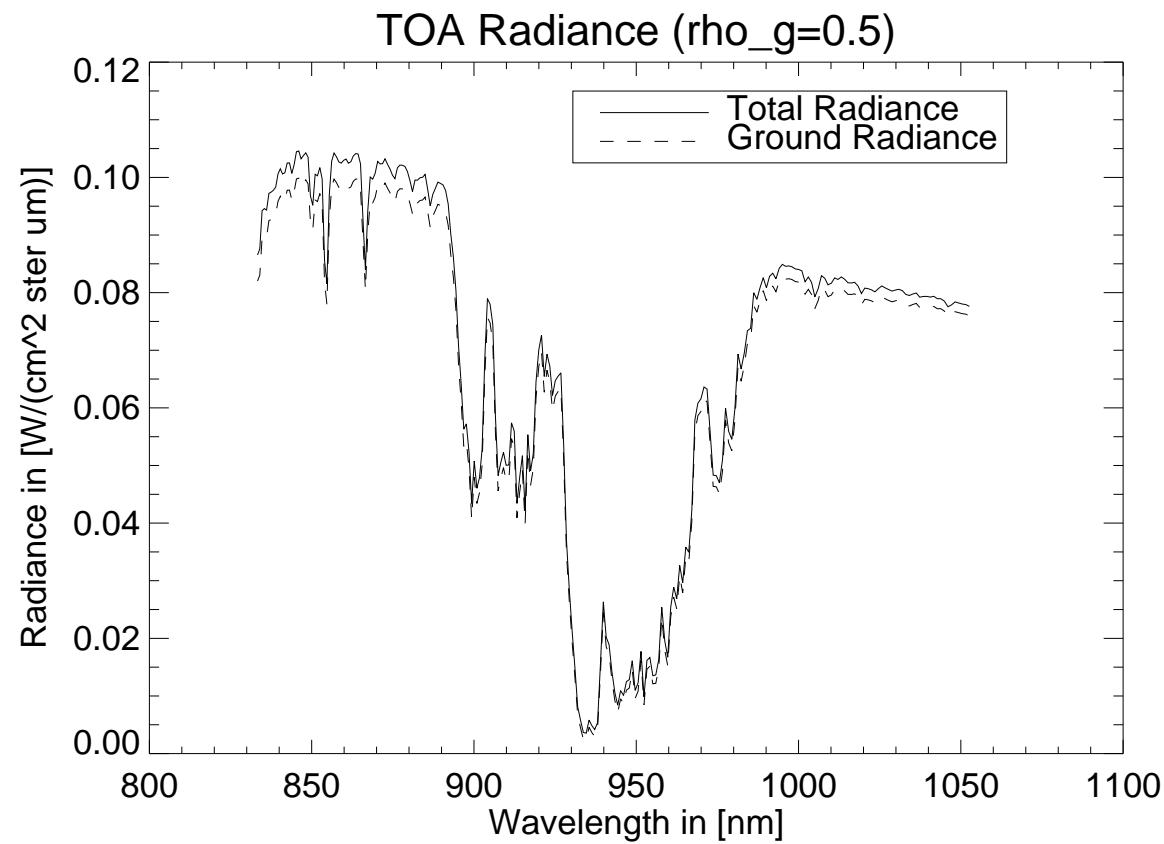
$$R_{CIBR}(\rho_{g,i} \approx 0.) \approx \frac{L_{p,m}(PW)}{w_{r1}L_{p,r1} + w_{r2}L_{p,r2}}. \quad (8)$$

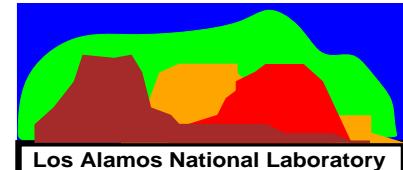
Thus $R_{CIBR} \approx L_{p,m}(PW) = L_{h,m}[1 - T_m^*(PW)] \neq T_m(PW)$.



BRIGHT TARGET CIBR:

$$R_{CIBR}(\rho_{g,i} \approx 1.) \approx \text{Const } T_m(PW). \quad (9)$$





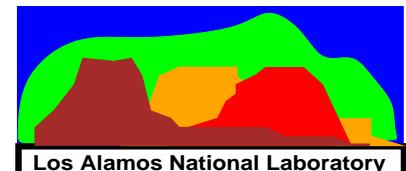
COMPARISON CIBR AND APDA

PROCEDURE:

Computed irradiances, transmissions and path radiance (with MODTRAN3 using the DISORT option).

PARAMETERS:

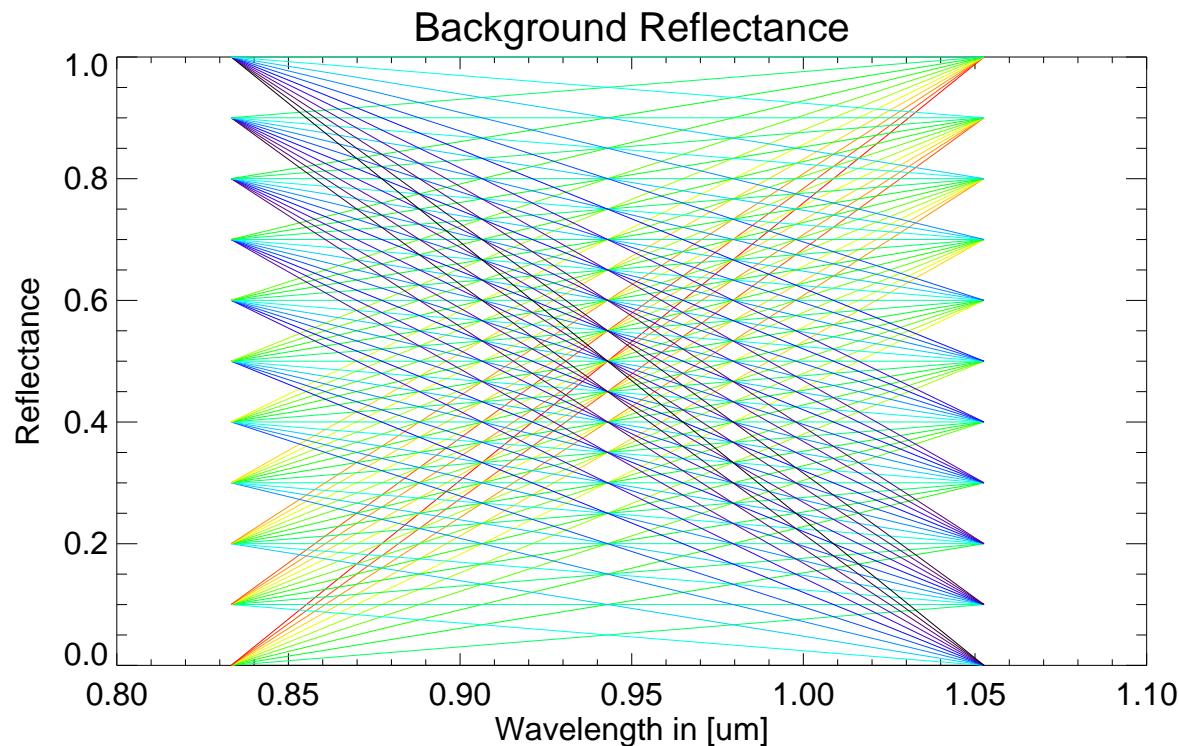
- Atmospheric state was mid-latitude summer,
- Visibility of 23 km,
- Columnar water vapor was fixed at 2.4 g/cm^2 ,
- Target height was at 0.4 km,
- Sun zenith at 40 degrees and
- Spectral resolution $\approx 1 \text{ nm}$.



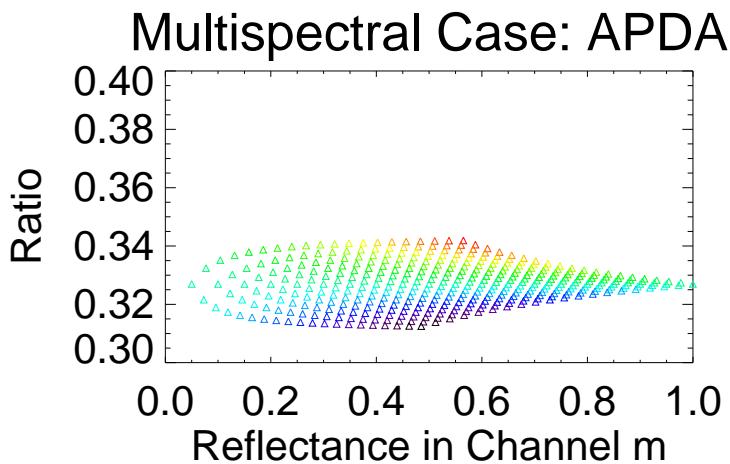
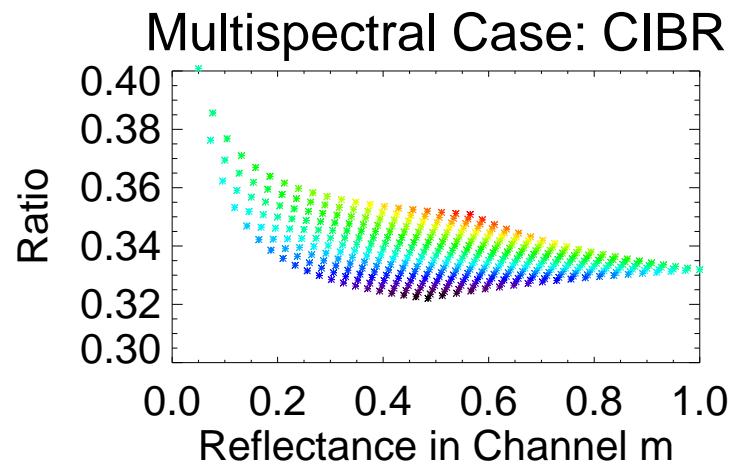
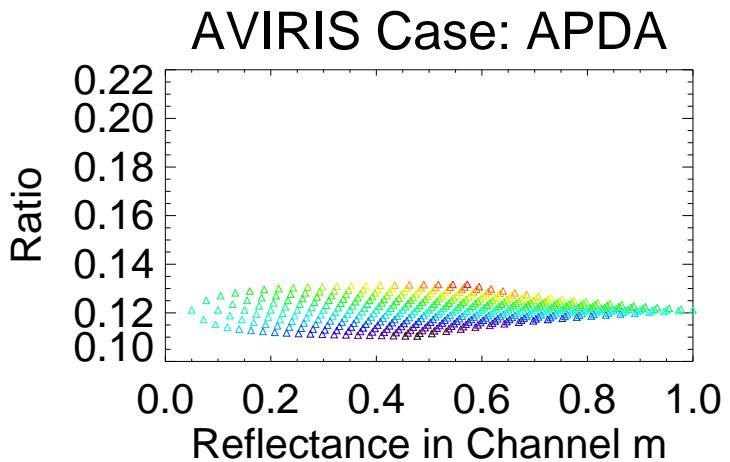
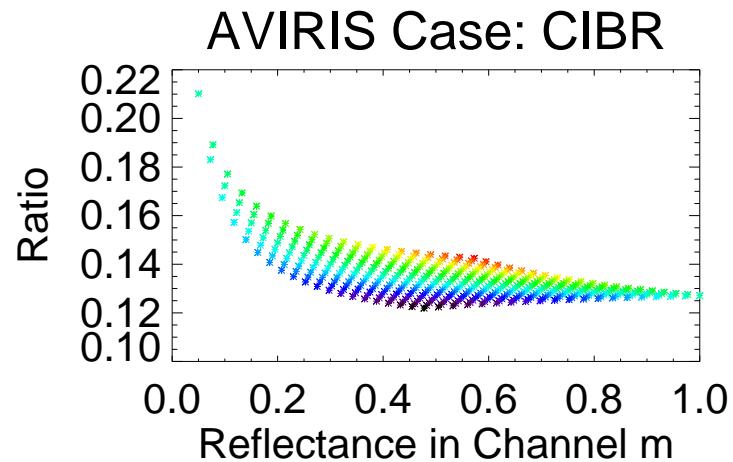
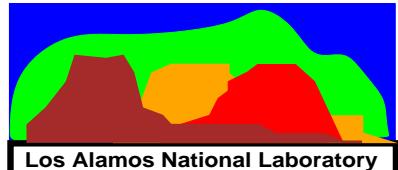
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- The ground reflectances $\rho_{g,1}$ and $\rho_{g,2}$ was changed from 0.05 to 1. in steps of 0.05:

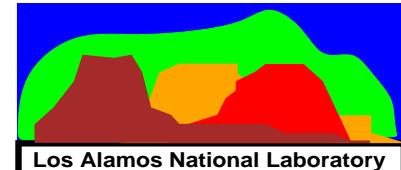
$$\rho_g(\lambda) = \rho_{g,1} + \frac{\rho_{g,2} - \rho_{g,1}}{\lambda_{max(r2)} - \lambda_{min(r1)}} \lambda - \lambda_{min(r1)}. \quad (10)$$



Back ground reflectances (color indicates slope).



CIBR and APDA as a function of band-averaged ground reflectance for a 10 nm bandwidth instrument (AVIRIS: $r_1=0.869-0.879$, $m=0.936 - 0.946$ and $r_2=0.994-1.004 \mu\text{m}$) and a multispectral instrument ($r_1=0.86-0.89$, $m=0.91-0.97$ and $r_2=0.99-1.04 \mu\text{m}$).



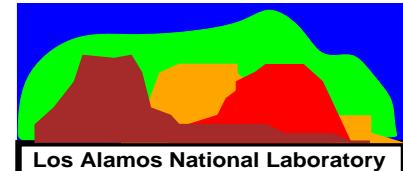
BACKGROUND/WATER VAPOR EFFECTS ON CIBR/APDA

GOAL: Test the behavior of CIBR and APDA techniques over spectrally varying backgrounds
SPECTRAL DATA BASES:

- 190 mineral spectra (JPL/Univ. of Colorado)
 - 246 mineral and vegetation spectra (USGS, Denver, <http://speclab.cr.usgs.gov/>)
 - 125 simulated vegetation spectral data base with variable leaf water content (PROSPECT and radiosity models used)
- ⇒ 562 spectra (includes zero reflectance background)

PROCEDURE:

- Re-sampled spectra at 2.5 nm sampling distance.
- Compute the TOA radiance over the water vapor band centered on 940 nm.
- Vary water vapor amounts from 0.05 to 5 g/cm^2 in 12 steps (only data from 1 to 4 g/cm^2 was used).



- Atmosphere had a constant visibility of 20 km with continental aerosols.
- Target height was set at sea level.
- Sensor located above the atmosphere.

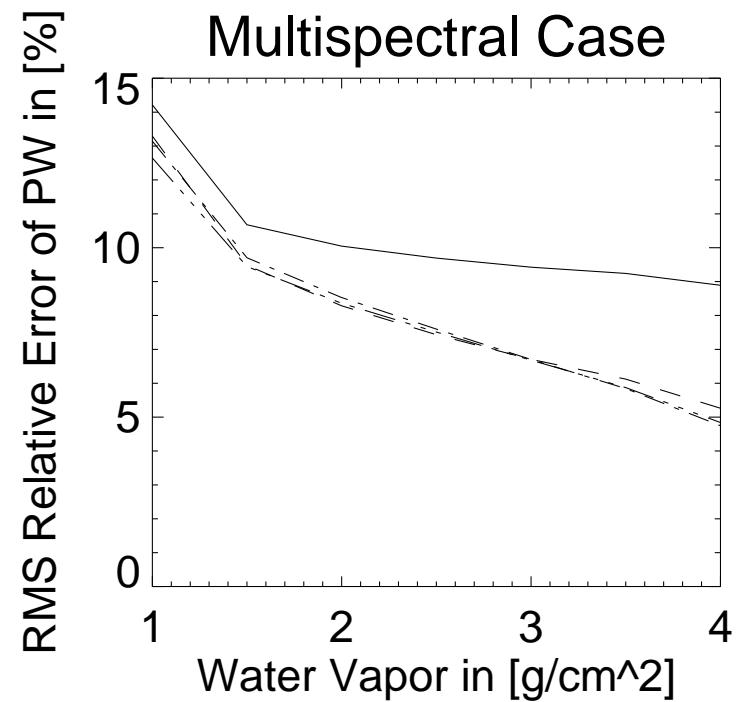
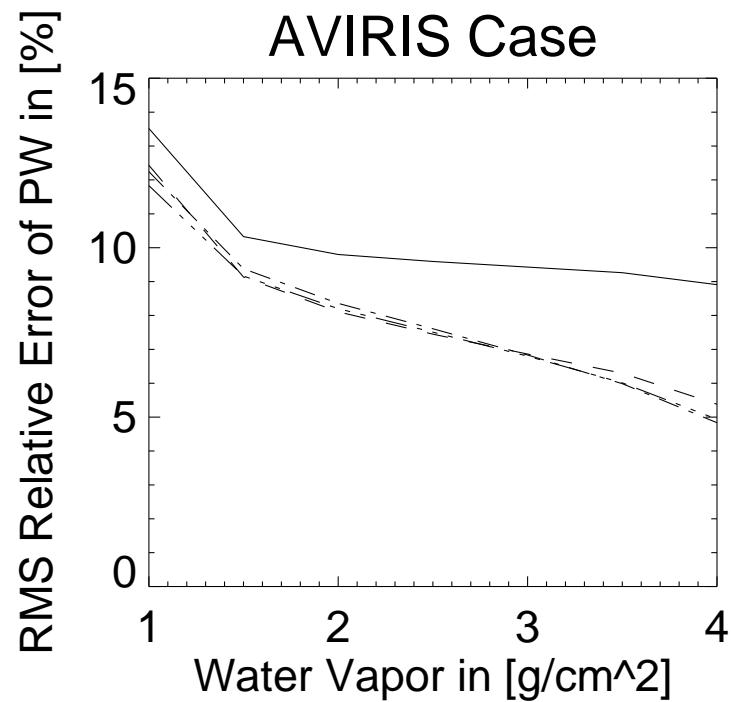
RMS relative error in percent:

$$\varepsilon(PW_j) = 100 \sqrt{\frac{1}{N} \sum_{i=1}^N \left[\frac{(PW_{i,est} - PW_{j,true})}{PW_{j,true}} \right]^2}$$

in water vapor for all $N = 562$ reflectance spectra as a function of water vapor.

4 TECHNIQUES:

1. **CIBR**: Original CIBR equation (7).
2. **APDA**: Regular APDA equation (6) using a fixed water vapor amount of 2.5 g/cm^2 to compute the path radiance $L_{p,m}$.
3. **APDA (optimal)**: Equation (6) with computed water vapor dependent path radiance $L_{p,m}(PW)$.
4. **APDA (iterative)**: Equation (6) with the iterative scheme (5 iterations).



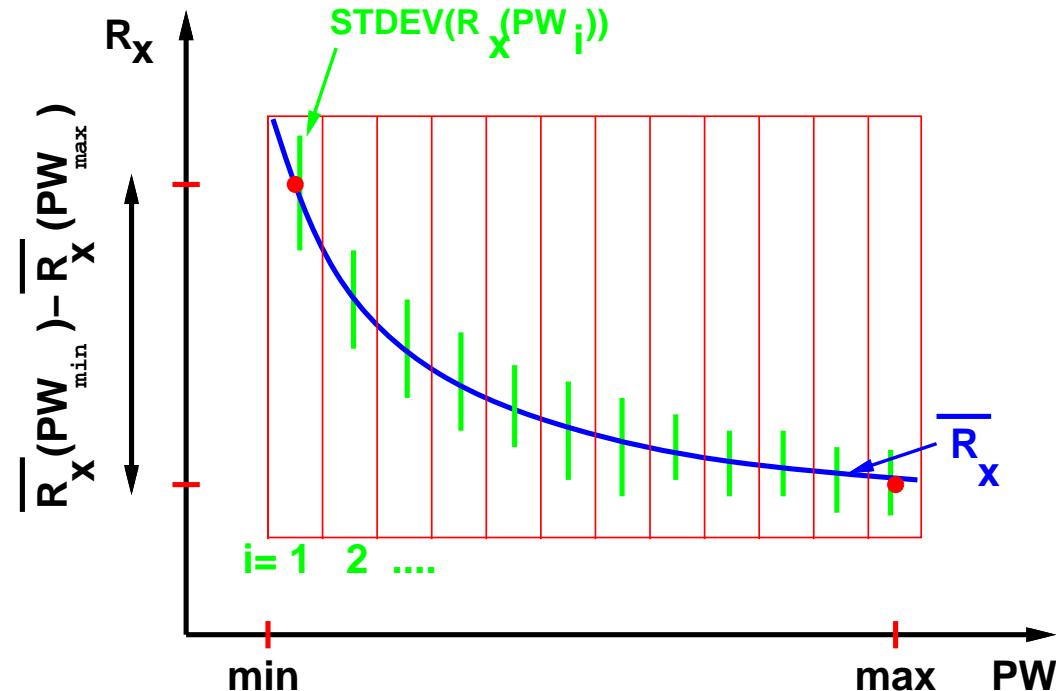
— CIBR - - - APDA - - - - APDA (optimal) - - - - - APDA (iterative)

RMS relative error $\varepsilon(PW_j)$ in % in water vapor for all 562 reflectance spectra as a function of water vapor for four different water vapor retrieval techniques.

QUASI SIGNAL TO NOISE RATIO (SNR):

$$SNR(R_x(PW)) = \frac{\bar{R}_x(PW_{min}) - \bar{R}_x(PW_{max})}{\sigma(R_x(PW))},$$

where $x = \{\text{CIBR, APDA, APDA(optimal), APDA(iterative)}\}$, (11)



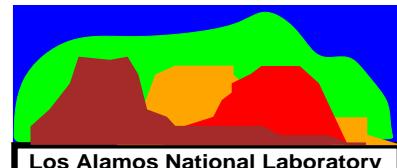
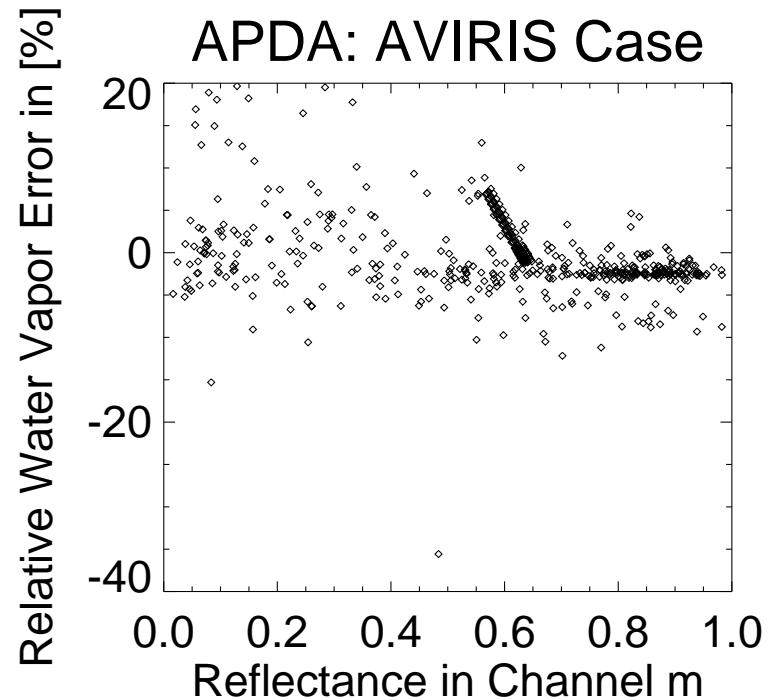
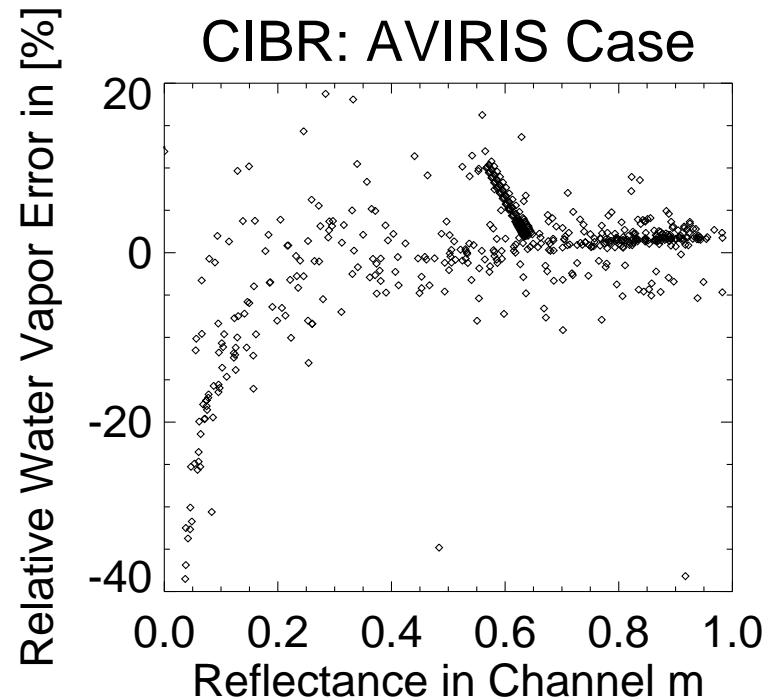


Table 1: SNR comparison

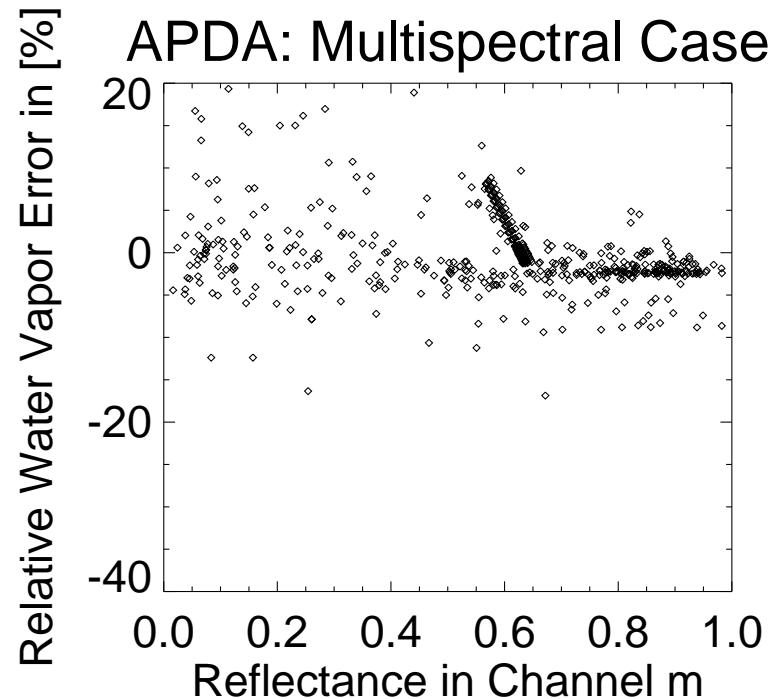
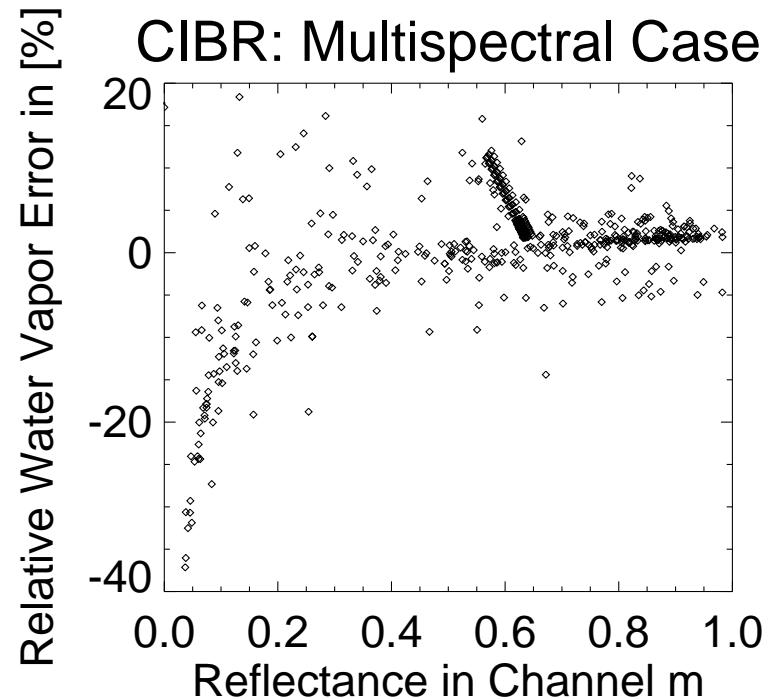
Case:	AVIRIS				Multispectral		
	Range of R	$\sigma(R)$	$SNR_{min/max}$	Range of R	$\sigma(R)$	$SNR_{min/max}$	
CIBR	0.238	0.01768	12.3-13.9	0.233	0.01743	12.0-14.0	
APDA	0.248	0.01277	13.6-24.2	0.243	0.01274	13.1-24.4	
APDA (optimal)	0.240	0.01217	13.9-26.6	0.235	0.01216	13.5-26.6	
APDA (iterative)	0.241	0.01233	13.9-26.3	0.237	0.01230	13.5-26.3	

Table 2: Percentage of Materials above 5% and 10% RMS Relative Water Vapor Error

Retrieval Method	AVIRIS 5%	Multispectral 5%	AVIRIS 10%	Multispectral 10%
CIBR	30.6	32.6	13.9	15.6
APDA	21.9	22.4	6.4	5.7
APDA (optimal)	21.7	22.9	6.2	5.7
APDA (iterative)	21.0	21.7	6.2	5.7



Relative water vapor errors over 562 backgrounds as a function of band-averaged ground reflectance for a 10 nm bandwidth instrument (AVIRIS). Note the lined up points near 0.6 reflectance are from canopy spectra.



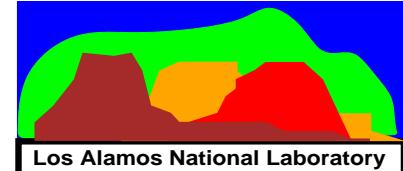
Relative water vapor errors over 562 backgrounds as a function of band-averaged ground reflectance for a multi-spectral instrument. Note the lined up points near 0.6 reflectance are from canopy spectra.

Table 3: Percentage of Materials above 10% RMS Relative Water Vapor Error (AVIRIS Case)

Mineral	$\rho_{g,m}$	$\frac{\rho_{g,r2} - \rho_{g,r1}}{\rho_{g,r2} + \rho_{g,r1}}$	$R_{CIBR}(\rho_{g,r1}, \rho_{g,m}, \rho_{g,r2})$	$PW_{rel.err.,iter}$ in [%]
ANTHOPHYLLITE-IN-8A	0.559	0.013	-0.06	12.98
ANTLERITE-SO-11A	0.149	0.125	-0.08	18.22
AUGITE-IN-15A	0.079	0.345	-0.07	18.90
Axinite	0.173	-0.65	-0.29	67.28
Azurite	0.065	0.238	-0.08	20.52
BUDDINGTONITE-NHB2301	0.550	0.035	0.009	-10.2
Beryl	0.671	0.204	0.050	-10.4
Bronzite	0.134	0.262	-0.27	70.92
Chrysocolla	0.093	0.301	-0.07	18.06
Copiapite	0.332	0.211	-0.07	17.75
CUMMINGTONITE-IN-6A	0.128	-0.05	-0.10	19.66
DICKITE-PS-3A	0.055	-0.05	-0.09	15.07
ENSTATITE-IN-10B	0.295	0.159	-0.16	42.18
FAYALITE-NS-1A	0.089	-0.18	-0.09	14.95
H ₂ O-Ice	0.769	-0.06	0.038	-11.1
HEMATITE-FE2602	0.231	0.236	-0.11	22.92
Hypersthene	0.415	0.121	-0.13	33.47
Jarosite	0.283	0.078	-0.09	19.51
Lepidocrosite	0.245	0.009	-0.08	16.45
Monazite	0.483	0.170	0.163	-35.5
MAGNESIOCHROMITE-O-8A	0.159	0.102	-0.05	10.81
MOLYBDENITE-S-11A	0.254	0.191	0.054	-10.5
Neodymium-Oxide	0.917	0.201	0.177	-40.7
NONTRONITE-PS-6D	0.339	0.039	-0.05	10.13
Praseodymium-Oxide	0.056	0.266	-0.07	16.93
TOURMALINE-DRAVITE-S-CS-1A	0.083	-0.10	0.059	-15.3
TREMOLITE-AMT3001	0.701	-0.09	0.006	-12.1
Samarium-Oxide	0.797	-0.03	-0.11	22.08
Siderite	0.113	-0.20	-0.08	13.02
Tephroite	0.138	-0.07	-0.07	12.55
Vesuvianite	0.628	0.014	-0.04	10.04

Table 4 : Percentage of Materials above 10% RMS Relative Water Vapor Error (Multispectral Case)

Mineral	$\rho_{g,m}$	$\frac{\rho_{g,r2}-\rho_{g,r1}}{\rho_{g,r2}+\rho_{g,r1}}$	$R_{CIBR}(\rho_{g,r1}, \rho_{g,m}, \rho_{g,r2})$	$PW_{rel,err.,iter}$ in [%]
ANTHOPHYLLITE-IN-8A	0.559	0.013	-0.06	12.64
ANTLERITE-SO-11A	0.149	0.125	-0.10	14.22
Augite	0.290	-0.19	-0.02	10.63
Axinite	0.173	-0.65	-0.22	86.29
Azurite	0.065	0.238	-0.11	13.26
Beryl	0.671	0.204	0.020	-16.8
Bronzite	0.134	0.262	-0.29	62.32
BUDDINGTONITE-NHB2301	0.550	0.035	0.004	-11.2
Copiapite	0.332	0.211	-0.09	10.74
Cuprite	0.157	0.115	0.021	-12.3
CUMMINGTONITE-IN-6A	0.128	-0.05	-0.09	21.56
DICKITE-PS-3A	0.055	-0.05	-0.08	16.73
ENSTATITE-IN-10B	0.295	0.159	-0.18	36.64
FAYALITE-NS-1A	0.089	-0.18	-0.07	20.61
HEMATITE-FE2602	0.231	0.236	-0.14	15.02
Hypersthene	0.415	0.121	-0.14	29.28
Jarosite	0.283	0.078	-0.10	16.97
Lepidocrosite	0.245	0.009	-0.08	16.17
Monazite	0.483	0.170	0.135	-41.4
MOLYBDENITE-S-11A	0.254	0.191	0.025	-16.3
Neodymium-Oxide	0.917	0.201	0.144	-48.2
Samarium-Oxide	0.797	-0.03	-0.11	23.24
Siderite	0.113	-0.20	-0.05	19.34
Sphalerite	0.466	0.169	0.003	-10.6
SIDERITE-COS2002	0.204	-0.24	-0.05	15.01
TOURMALINE-DRAVITE-S-CS-1A	0.083	-0.10	0.075	-12.3
TRIPHYLITE-P-4A	0.440	-0.30	-0.02	18.89
Tephroite	0.138	-0.07	-0.06	14.93



CLASSIFICATIONS OF BACKGROUND SPECTRA:

DARK: If reflectance in channel m below 0.1

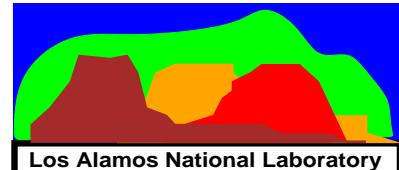
SLOPED: If

$$R_{slope} = \frac{\overline{\rho}_{g,r1} - \overline{\rho}_{g,r2}}{\overline{\rho}_{g,r1} + \overline{\rho}_{g,r2}} > 0.05.$$

NON-LINEAR: $R_{non-linear} < 0.95$ and $R_{non-linear} > 1.05$

$$R_{non-linear} = \frac{\overline{\rho}_{g,m}}{w_{r1}\overline{\rho}_{g,r1} + w_{r2}\overline{\rho}_{g,r2}}$$

Note: a negative water vapor error corresponds to an absorption feature, a positive error is due to a convex reflectance spectrum near 940 nm.



CONCLUSIONS

- An efficient technique to determine the amount of columnar water vapor has been derived from a modified radiative transfer equation.
- The technique seems to work much better than the current CIBR techniques which neglect the effects of path radiance.
- We show how the CIBR and APDA behave over dark, bright and spectrally variable backgrounds.
- A large number of mineral, man-made and simulated vegetation spectra were used and the relative water vapor error lies within $\pm 5\%$ for most reflectance spectra.
- A challenge remains to determine water vapor over dark surfaces such as water since the path radiance is now the only quantity containing information about the water vapor.
- More work is also needed to retrieve water vapor in rough terrain.
- The presented techniques may also be useful to retrieve other gases such as O_2 (\sim height).